A new connection between greenhouse warming and stratospheric ozone depletion

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The direct radiative effects of the build-up of carbon dioxide (CO_2) and other greenhouse gases have led to a gradual cooling of the stratosphere with largest changes in temperature occurring in the upper stratosphere, well above the region of peak ozone (O_3) concentration[1]. Cooling of the upper stratosphere during the past several decades would lead to slightly higher concentrations of O_3, but this forcing has been masked by depletion of upper stratospheric O_3 driven by the release of industrial chlorofluorocarbons (CFCs) (ref. 2). It has also been suggested that the abundance of O_3 in the lower stratosphere may be reduced on longer time scales due to changes in circulation induced by the so-called "doubled CO_2" environment[3]. On page XXX of this issue, Shindell *et al.*[4] describe a new, previously unappreciated connection between greenhouse gases and O_3 for the contemporary lower stratosphere: the possibility that increasing concentrations of greenhouse gases may currently be leading to colder, more stable vortex circulations in winter, accelerating the chemical removal of O_3 at high latitudes. This hypothesis may have important implications for public policy. The authors' calculations suggest that, because of the build-up of greenhouse gases, the total column abundance of O_3 in the Arctic vortex will continue to decrease for about 15 years after levels of stratospheric chlorine begin to decline.

Rapid loss of O_3 throughout the winter polar vortices occurs when the following conditions are met: high concentrations of chlorine monoxide (ClO), low temperatures, and relatively long periods of daylight. The unreactive reservoirs HCl and $ClNO_3$ are converted to ClO by reactions on the surfaces of polar stratospheric clouds (PSCs) that form when temperature drops below a critical threshold. Sunlight is required for catalytic removal of O_3, but sunlight also leads to the suppression of elevated concentrations of ClO. Maintenance of high concentrations of ClO until equinox requires either temperatures persistently low enough to suppress concentrations of gas phase HNO_3, which photolyzes and eventually converts ClO to $ClNO_3$, or temperatures intermittently low enough to allow repeated exposure of air to heterogeneous processing on PSCs. More stable vortex circulations (i.e., greater isolation) typically lead to colder temperatures and a stronger association between local chemical loss and the column abundance of O_3.

Ozone concentrations in the Arctic polar vortex reached unusually low values during the early springs of 1996 and 1997 (ref. 5, 6, 7). Compared to the Antarctic vortex, which experiences elevated concentrations of ClO until equinox and massive loss of O_3 on an annual basis, concentrations of ClO in the Arctic vortex are usually too low by early March for sustained rapid loss of O_3 (ref. 8). The rapid loss of Arctic ozone during late winter and early spring of 1995/96 and 1996/97 has been associated with observations of enhanced levels of ClO (ref. 9), suppressed levels of HCl (ref. 5), unusually low temperatures during early March[5,6,7,10], and more stable vortex circulations[10]. Conditions during these two years have built upon the general (but not monotonic) trend in the Arctic towards lower abundances of total column O_3 in March and lower temperatures in late February/early March during recent years, as illustrated in Figure 1, even though the burden of stratospheric chlorine has stopped rising due to international legislation that has phased out the use of CFCs[11].

Shindell *et al.*[4] provide a provocative explanation for the unusually cold, stable Arctic vortices during early March of recent years – a decrease in the poleward propagation of planetary waves, driven by increased concentrations of greenhouse gases. The decrease in planetary wave activity in their model is driven by a decline in the latitudinal temperature gradient near the tropopause. A feedback involving decreased absorption of solar radiation due to less O_3 exacerbates the situation, leading to a non-linear response of temperature to climate forcing. An analysis of temperature fields from the National Center for Environmental Prediction (NCEP) has shown that the low Arctic temperatures during March 1997 were likely due to a significant reduction in planetary wave activity[10]. This hypothesis may also offer an explanation for the rapid acceleration in the severity of the Antarctic O_3 hole during the 1980s.

The hypothesis of Shindell *et al.*[4] must be viewed as somewhat speculative given the difficulty general circulation models (GCMs) have in properly simulating both temperatures in the polar region and the non-linear wave-wave interactions that lead to poleward transport of heat and momentum[3,12]. Reliable predictions of stratospheric wave transport are critically dependent on the proper simulation of the circulation of the upper troposphere[3,12,13]. The detailed dynamical conditions that lead to low temperatures within the Arctic vortex vary from year-to-year[7,10,13,14] and are inherently difficult to simulate using a GCM. Indeed, the primary conclusion of Shindell *et al.*[4] is model dependent: some but not all other GCMs find similar decreases in planetary wave activity as the concentrations of greenhouse gases rise[4]. Nonetheless, during the past decade there has been an apparent trend towards colder conditions later in the season[6,7,10,14], lower abundances of total column O_3 (ref. 6), and more extensive chemical removal of lower stratospheric O_3 (ref. 5, 6, 9) that resembles the predictions of Shindell *et al.*[4]

The hallmark of the Arctic vortex is large year-to-year variability in temperature, the concentration of ClO in February and March, and the degree of chemical loss of O_3. The Arctic winter of 1997/98 has been fairly warm, with considerably less chemical loss of O_3 than occurred in the previous 5 winters[15]. This behaviour is not necessarily inconsistent with the model of Shindell *et al.*[4], which predicts less frequent early warmings of the Arctic vortex but not the complete cessation of such events. However, the winter of 1997/98 certainly complicates ascribing a climatic influence to the changes in temperature and O_3 that have occurred during the previous 5 winters. It is clear that predicting the future course of both Antarctic and Arctic O_3 is contingent upon gaining a better understanding of the factors that regulate the temperature of the polar vortices, and it is imperative that the hypothesis of Shindell *et al.*[4] be tested by further analyses of atmospheric observations as well as by additional theoretical studies.

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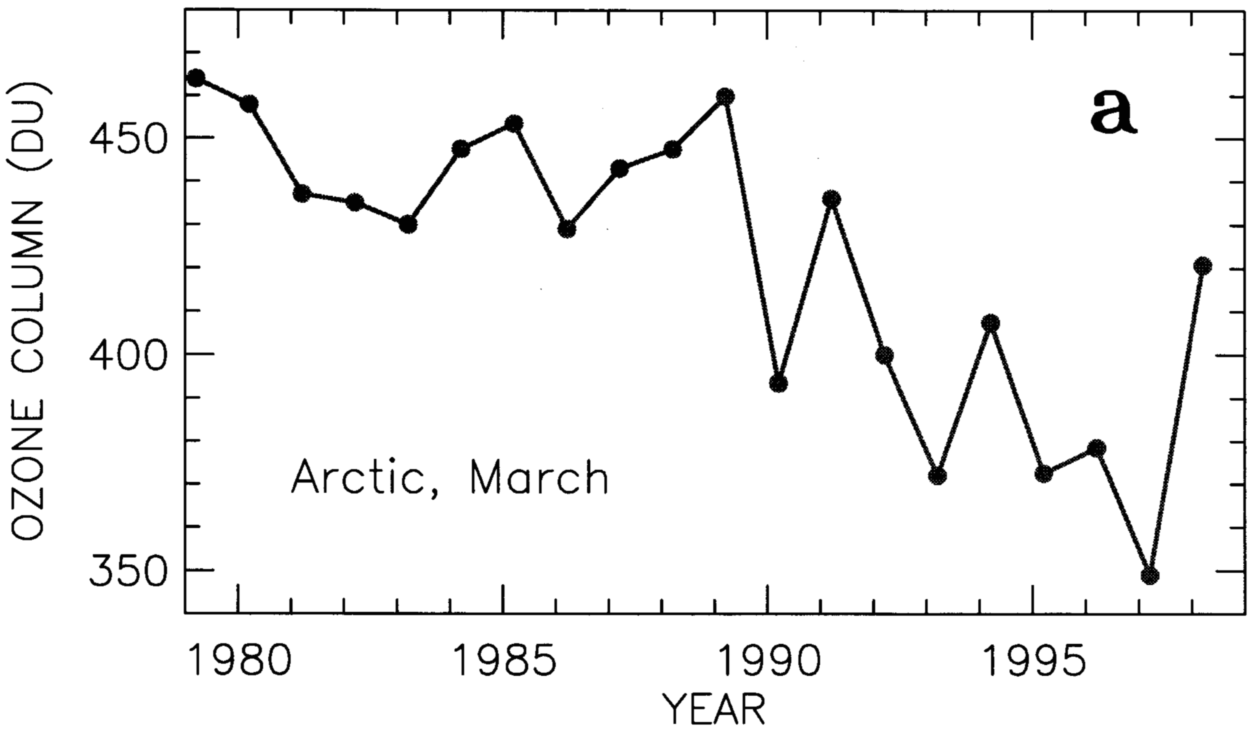
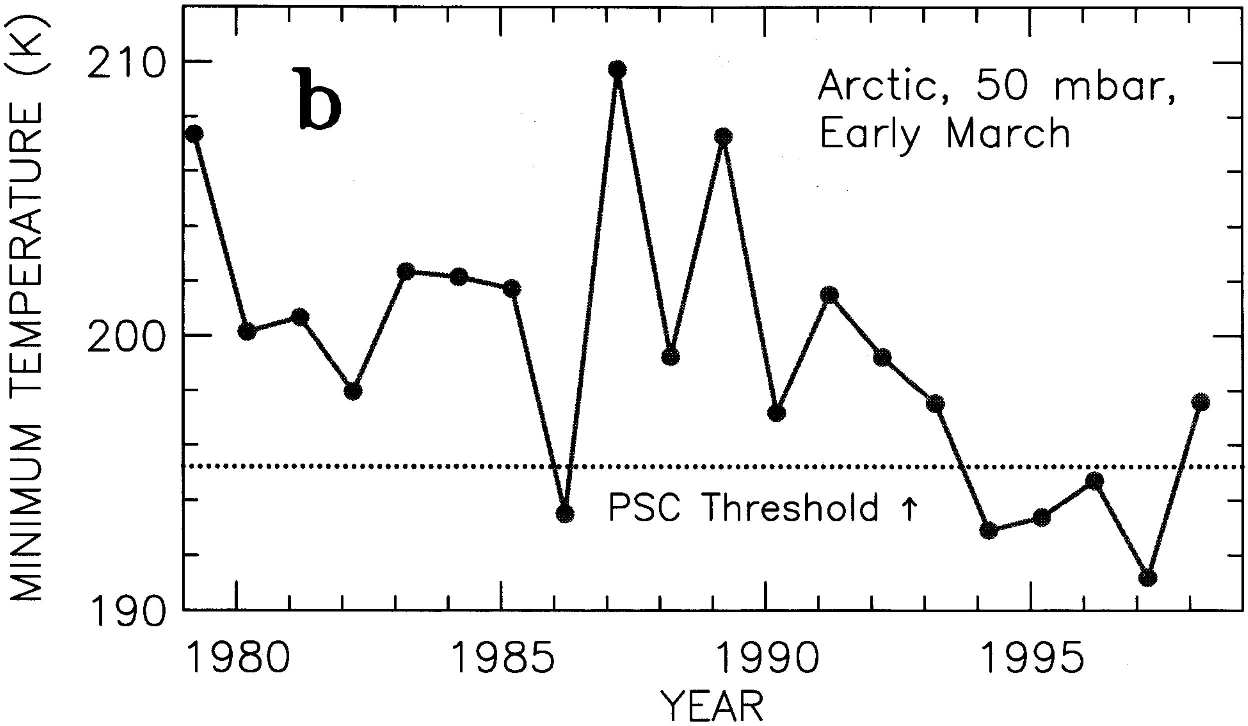
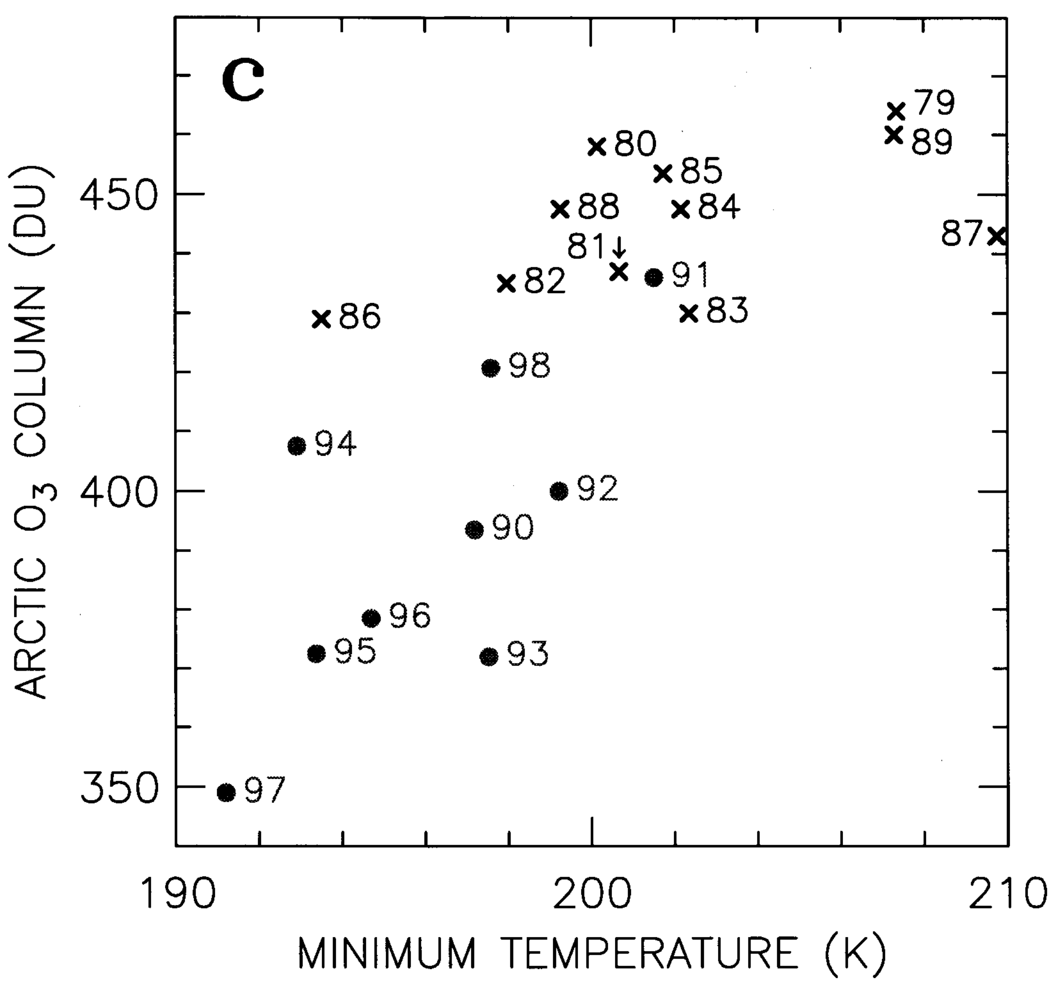
Figure 1 Time series of the average total ozone column in the Arctic (63 to 90°N) during March from Newman *et al.*[6] (*panel a*) and the minimum temperature on the 50 mbar pressure level in the Arctic vortex during the first 2 weeks of March based on data from NCEP (*panel b*). Column O_3 data for 1998 are from Earth Probe TOMS measurements through 24 March 1998, the latest date for which observations are available at the time of writing. A scatter diagram of these observations is also shown, with the data labeled according to the year of observation (*panel c*). Shindell *et al.*[4] show that rising concentrations of greenhouse gases may be the cause of the colder conditions in recent years, accelerating the chemical loss of O_3 by ClO derived from industrial CFCs. Observations for 1998 are preliminary.


a
Arctic, March
OZONE COLUMN (DU)
450
400
350
1980
1985
1990
1995
YEAR



b
Arctic, 50 mbar,
Early March
PSC Threshold ↑
MINIMUM TEMPERATURE (K)
210
200
190
1980
1985
1990
1995
YEAR



c
ARCTIC O_3 COLUMN (DU)
MINIMUM TEMPERATURE (K)
350
400
450
190
200
210
79
80
89
85
88
84
87
81
82
91
83
86
98
94
92
90
96
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93
97